Modelling the potential for multi-location in-sewer heat recovery at a city scale under different seasonal scenarios

Mohamad Abdel-Aal[1*], Alma Schellart [1], Stefan Kroll[2], Mostafa Mohamed[3], and Simon Tait[1].

[1] *Pennine Water Group, Department of Civil and Structural Engineering, University of Sheffield, Mappin Street, Sheffield, S1 3JD, UK.*
[2] *Aquafin NV, Dijkstraat 8, 2630 Aartselaar, Belgium*
[3] *School of Engineering, University of Bradford, Bradford, BD7 1PD UK*

**Corresponding author's email: m.abdel-aal@sheffield.ac.uk*

Abstract

A computational network heat transfer model was utilised to model the potential of heat energy recovery at multiple locations from a city scale combined sewer network. The uniqueness of this network model lies in its whole system validation and implementation for seasonal scenarios in a large sewer network. The network model was developed, on the basis of a previous single pipe heat transfer model, to make it suitable for application in large sewer networks and its performance was validated in this study by predicting the wastewater temperature variation in a sewer network. Since heat energy recovery in sewers may impact negatively on wastewater treatment processes, the viability of large scale heat recovery across a network was assessed by examining the distribution of the wastewater temperatures throughout the network and the wastewater temperature at the wastewater treatment plant inlet. The network heat transfer model was applied to a sewer network with around 3000 pipes and a population equivalent of 79500. Three scenarios; winter, spring and summer were modelled to reflect seasonal variations. The model was run on an hourly basis during dry weather. The modelling results indicated that potential heat energy recovery of around 116, 160 & 207 MWh/day may be obtained in January, March and May respectively, without causing wastewater temperature either in the network or at the inlet of the wastewater treatment plant to reach a level that was unacceptable to the water utility.

Key words: Heat recovery, heat transfer modelling, wastewater temperature prediction, clean thermal energy

1 Introduction

The potential heat available for recovery from sewers in the UK is thought to be significant, when estimated theoretically, due to the high volumes of collected wastewater and the relatively high wastewater temperatures found throughout the UK's combined and foul sewer networks. The UK's 347,000km of sewers (Defra, 2002) are generally located in urban catchments where the domestic heat demand is estimated to be around 300 TWh/year (ECUK, 2017). Considering heat recovery will result in a 2°C wastewater temperature reduction (Buri & Kobel, 2005), the 11 billion litres of wastewater produced per day (Defra, 2002), would potentially result in up to 390 TWh of heat recovery per year. This estimate is based on the first law of thermodynamics, where the potential rate of heat recovery is the product of wastewater mass flow rate, its specific thermal capacity and the consequent temperature reduction, and assumes a 100% efficient heat recovery systems installed across all the UK's sewer networks.

The key technical challenge for efficient in-sewer heat recovery is to enable heat recovery sufficiently close to points of local demand. To meet this challenge it is essential to quantify the impact of simultaneous heat recovery at multiple locations within a sewer network. This "locality" constraint can reduce the overall system potential. For example, in Austria, Kretschmer et al. (2015) estimated that 10% of Austrian houses can benefit from heat recovered from wastewater. Another barrier for recovering heat from sewers is that any reduction in wastewater temperature may cause difficulties with treatment processes and incur extra costs at the end of system wastewater treatment plant (WwTP). It is therefore important to ensure that even with multiple locations of heat recovery, the wastewater temperature reduction is limited at the inlet to the WwTP. The nitrification process at the WwTP may be compromised by low wastewater temperatures, as demonstrated by Shammas (1986), who tested the impact of varying the wastewater temperatures, from 4 to 35°C, on the nitrification quality and concluded that nitrification is much more effective at temperatures in the upper part of this range, i.e. between 25 and 35°C. This finding is in line with a number of other studies summarised in Metcalf & Eddy (2004), who reported that the optimum wastewater temperature for nitrification was estimated to be between 25 and 35°C. Previous authors such as Wanner et al. (2005) examined the impact of the reduction in temperature on wastewater nitrification and concluded that 1°C reduction in wastewater temperature may reduce the nitrifier growth by 10%. Such a reduction would require a 10% increase in the sludge retention time, to maintain the same nitrification quality achieved at the unadjusted wastewater temperatures.

Previous studies have examined the variation in wastewater temperature in order to estimate the potential of heat energy recovery and its impact on the treatment processes in WwTPs. Early work by Bischofsberger et al. (1984) measured wastewater temperatures in Hamburg, Germany, for a year at five locations in a combined sewer network, and observed that the wastewater temperatures varied between 7°C and 28°C during the year. This temperature range was close to that observed in other in-sewer wastewater temperature measurements reported in Dürrenmatt and Wanner (2008), Schilperoort and Clemens (2009), Cipolla and Maglionico (2014), Abdel-Aal (2015) and Simperler (2015) in a number of combined sewer networks across Europe.

Some studies have used simple relationships to estimate the impact of recovering heat energy on in-sewer wastewater temperature, Kretschmer et al. (2016) estimated the potential heat energy recovery to be a linear function of wastewater temperature, flow rate, temperature reduction and the heat capacity of water. No estimate was made, by these authors, of the heat flux between the flowing wastewater and the in-sewer air and the surrounding soil. Assessing the impact of heat energy recovery from a sewer pipe has led some authors to develop more complex computational models to predict the wastewater temperature variation along a sewer pipe taking into account heat flux into the surrounding soil and into the in-sewer air above the wastewater flow. These models were developed for single pipes but by linking pipe sections they could be used to estimate the cumulative effect along extended sewer pipes (Dürrenmatt, 2006; Dürrenmatt and Wanner, 2008; Dürrenmatt and Wanner, 2014; Abdel-Aal et al., 2014; Abdel-Aal, 2015). The model developed by Dürrenmatt and Wanner (2008), named TEMPEST, was the first capable of predicting wastewater temperature in successive sewer pipes. Published studies have shown that TEMPEST was implemented in a single string of sewer pipes; 1.85km long (Dürrenmatt and Wanner, 2014) and 3km long (Sitzenfrei et al., 2017). The TEMPEST model was calibrated using a dataset collected over a 5 week period from 14th February to 22nd March 2008. Elías-Maxil et al. (2017) developed a parsimonious model based on TEMPEST yet excluded computation of the heat transfer between wastewater and in-sewer air. They claimed that the heat flux between the wastewater and in-sewer air was not significant and could be ignored.

Elías-Maxil et al. (2017) used flow and temperature data collected in a 300 m long pipe to calibrate and validate their model by adding hot water at a temperature of 50°C for six hours instead of simulating the temperature variation of the wastewater. Abdel-Aal (2015) utilised measured flow and wastewater data collected over a four month period in a small number of pipes within a combined sewer network to analyse the sensitivity of the calibration parameters in the empirical equations describing the heat flux between the in-sewer air and the wastewater and between the wastewater and surrounding soil. The calibration parameters were varied from 10% to 400% of their default values, found in literature, and the impact of these variations on the predicted downstream wastewater temperature was quantified. Increasing the heat transfer coefficient between wastewater and in-sewer air by four times resulted in a 0.4°C variation, which was the largest change among all other empirical heat transfer parameters taken into account, i.e. soil thermal conductivity, soil penetration depth and pipe wall thermal conductivity. Hence, the sensitivity analysis indicated that the heat flux between the wastewater and the in-sewer air should not be ignored if an accurate estimate of the reduction in wastewater temperature along a sewer pipe is to be obtained.

The simulations reported in this paper utilised a network computational heat transfer model developed by Abdel-Aal (2015), and validated in this work, which is able to predict in-pipe wastewater temperatures throughout a large sewer network. The network heat flux model links an in-pipe heat transfer model, accounting for air-wastewater, wastewater-pipe and wall-soil heat fluxes with a hydrodynamic sewer network model. The model of Elías-Maxil (2015) was implemented on a single sub-catchment in a sewer network and was used to predict in-pipe wastewater temperatures. It was not utilised to investigate the impact of several locations of heat recovery on in-sewer wastewater temperatures. The uniqueness of this work is the simultaneous modelling of heat recovery from multiple locations within a single network over long durations. This has allowed the assessment of the in-sewer heat recovery reliability from a real large sewer network over different periods within a year. Predicting the rate of heat recovery and assessing its reliability are keys to making a believable economic assessment.

2 Methodology

A heat transfer model was initially developed for a single sewer pipe and then modified and implemented in a large sewer network, hence 'single pipe' and 'network' heat transfer models are used in this paper to describe both model types respectively. This section briefly explains the method followed in the development of the single pipe heat transfer model and how it was initially calibrated and validated. The build-up, calibration and validation of the sewer network hydrodynamic model for the case study catchment is then described. Following these descriptions an explanation is given as to how the single pipe heat transfer model was further developed and then linked with the hydrodynamic sewer network model in order to deliver a network heat transfer model. The predictive performance of the network heat transfer model was then validated using collected field data from the case study catchment.

Calibration is defined in this paper as adjusting model parameters to minimise the differences between predictions and observations . The validation process quantified model accuracy by implementing the obtained calibrated parameters in model simulations and comparing predicted values with measured data that were independent of those used for calibration. In the case of validating the hydrodynamic model, after comparing measured and modelled flow rates and depths during dry weather flow days, head loss parameters were adjusted to take into account the local energy losses and hence, improve the model accuracy at specific locations. This section ends by explaining how the predicted wastewater temperatures, in the network and at the WwTP inlet, were employed to model the potential heat energy recovery at multiple locations on hourly basis, for different months.

2.1 The single pipe heat transfer model

This section briefly explains how a previously created single pipe heat transfer model was developed, calibrated and validated so that it was then suitable for use in this study.

2.1.1 Development of the single pipe heat transfer model

The aim of this single pipe model was to produce an efficient sub-model that can be ultimately used in a more complex model to obtain network temperature simulations while accounting for all the major heat transfer processes observed within a single sewer pipe. Implementing the first law of thermodynamics and accounting for the thermal convection between wastewater and in-sewer air and conduction between wastewater, at the invert level, and the surrounding soil through the pipe wall, the wastewater temperature variation along a single sewer pipe can be expressed by Equation 1, (Abdel-Aal, 2015).

$$T_{m+1} = T_m - \left(\frac{\frac{1}{R_{wa}}(T_m - T_{air}) + \frac{1}{R_{ws}}(T_m - T_{soil})}{\rho \times Q \times c_p} \Delta x \right) \qquad (1)$$

When heat was recovered upstream of a sewer pipe in the network, it was assumed that wastewater temperature at the point downstream of any heat energy recovery location is reduced as a result of the heat recovery process, which can be estimated using Equation 2.

$$T_{m+1} = T_m - \left(\frac{HR}{\rho \; Q \; c_p} \right) \qquad (2)$$

T is temperature (K), m is an expression of the wastewater temperature location within a longitudinal computational mesh along the pipe length, R is thermal resistivity (m.K/W) between wastewater and in-sewer air (wa) and between wastewater and soil (ws), Δx is the computational increment length stream-wise (m) based on dividing each pipe into 10 increments, ρ_w is the wastewater density (kg/m^3), Q is the wastewater volumetric flow rate (m^3/s) and c_p is the specific heat capacity for wastewater (J/kg.K), HR is the rate of heat recovered in Watts.

Equation 1 interprets the energy balance by expressing the thermal convection and conduction in terms of thermal resistivity which is a function of the wastewater velocity, its surface width and the pipe wetted perimeter which were ultimately computed using hydraulic data and pipe shapes retrieved from the sewer network hydrodynamic model.

The wastewater temperature was modelled with the assumption that the in-sewer pipe flow has a free surface. This is because typical DWF, in a sewer pipe, has a larger proportion of in-sewer air volume to that of wastewater. For example, the average measured wastewater depth to pipe diameter ratio was 8% in urban residential sewers and 42% in large sewer collectors (Abdel-Aal, 2015).

Edwini-Bonsu and Steffler (2006) installed a scrubber in a sewer pipe within a small network with 15 manholes to measure the influence of forced ventilation on the in-sewer air velocity by switching the scrubber on and off. Measured field data in the latter study showed that there was around a 10% variation in the in-sewer air velocity between trapped in-sewer air and forced ventilation conditions. Therefore, the effect of active air ventilation in the sewer pipes was neglected in the in-sewer air/wastewater convection based heat transfer model. The use of a conduction based heat transfer relationship between wastewater and the surrounding soil is based on the assumption that there is no slip conditions between wastewater and inner surface of the pipe wall, as detailed in Abdel-Aal (2015).

2.1.2 Calibration of the single pipe heat transfer model

The calibration of the single pipe heat transfer model was performed using data collected in four pipes of the case study catchment. Hydraulic data was logged every 2 minutes, and soil temperature was measured every 20 minutes, while the upstream and downstream wastewater and in-sewer air temperatures were recorded every 15 minutes in two larger collector sewers, and every 20 minutes in two smaller urban sewers. Such data monitoring frequencies were found reasonable and adequate to calibrate and validate the single pipe heat transfer model. The measured hydraulic and temperature data was logged continuously in February, March and May 2012 for sewer pipes located in the case study catchment. Wastewater temperatures were observed, by Tinytag (PBRF-5006-5m) sensors with ± 0.06°C accuracy and better than 0.05°C resolution.

The importance of simulating the heat transfer between wastewater and in-sewer air for the prediction of wastewater temperature variation, as mentioned above, led the authors to study and analyse the heat transfer process between wastewater and in-sewer air. This relation was represented in Equation 1 by the thermal resistivity between wastewater and in-sewer air (R_{wa}) and can be described by Equation 3.

$$R_{wa} = \frac{1}{h_{wa} \times b} \quad (3)$$

h_{wa} is the convective heat transfer coefficient between wastewater and in-sewer air ($W/m^2.K$), b is the surface width of wastewater running in a sewer pipe (m).

The traditional approach in estimating the heat transfer coefficient between water and air is through the use of an empirical relationship. Flinspach (1973) proposed a relation, which is a function of the relative wastewater velocity to that of in-sewer air, to estimate the heat transfer coefficient between wastewater and in-sewer air (h_{wa}). However, the origin and underlying assumptions of Flinspach's relation is not well recorded and it performed inconsistently. Hence, and in an attempt to improve the modelling accuracy, a new more physically based parameterisation was developed to incorporate the influence of the wastewater surface velocity, as it is associated with in-sewer air velocity (Edwini-Bonsu and Steffler, 2006) and depth, to estimate h_{wa}, using the dimensionless Froude number.

The soil penetration depth and soil thermal conductivity were also calibrated to estimate the thermal resistivity between wastewater and the surrounding soil (R_{ws}), which is given by Equation 4. This is because, in addition to the heat transfer between wastewater and in-sewer air, the single pipe heat transfer model was sensitive to the soil penetration depth and its thermal conductivity (Abdel-Aal, 2015). Moreover, measuring the soil thermophysical properties in the field was impractical and the relevant parameters had wide ranges in literature.

$$R_{ws} = \frac{t_p}{k_p \times wet.p} + \frac{d_s}{k_s \times wet.p} \qquad (4)$$

t_p is the pipe wall thickness (m), d_s is the soil penetration depth (m), k_p and k_s are the thermal conductivities for pipe wall material and soil respectively (W/m.K) and wet.p is the pipe wetted perimeter (m).

Dürrenmatt (2006) and Dürrenmatt and Wanner (2014) incorporated more parameters such as, Chemical Oxygen Demand (COD) and its degradation rate, in their TEMPEST model. However, variation of these parameters showed insignificant impacts (less than 0.2%) on the predicted wastewater temperature (Dürrenmatt, 2006). In order to develop a computationally efficient simulation for use in a large sewer network, the single pipe heat transfer model was developed using only relationships which were significant in terms of the predicted wastewater temperature. Calibration of the single pipe heat transfer model was achieved using optimisation tools in Matlab to minimise the root mean squared error (RMSE) for each month's dataset, using Equation 5. A time step of 2 minutes, at which hydraulic data was measured, was utilised for calibrating the single pipe heat transfer model.

$$RMSE = \sqrt{\frac{\sum_{j=1}^{N} (T_{M_j} - T_{P_j})^2}{N}} \qquad (5)$$

T is the wastewater temperature (°C), M and P stand for measured and predicted respectively, N is the total number of time steps and j is data point number.

The model error was also computed to assess the single pipe heat transfer model accuracy in terms of over and under prediction, which was the average predicted minus measured wastewater temperatures for a full month dataset.

2.1.3 Validation of the single pipe heat transfer model

Validation was carried out using independent datasets from that utilised for calibrating the single pipe heat transfer model. The validation data was measured in sewer sites with similar characteristics to those used for calibration, i.e. large collector and urban sewers, and in the same period, using identical sensor types described in section 2.1.2. The model validation was assessed by the RMSE and modelling errors in a similar manner described in section 2.1.2.

2.2 The hydrodynamic sewer network model

Hydraulic data, such as the wastewater flow rate, velocity and depth is necessary for simulating the in-sewer wastewater temperatures. Therefore, a hydrodynamic model built in Infoworks CS, was used to provide the hydraulic data for the case study sewer network. The Infoworks CS model used a numerical scheme to solve the Saint-Venant and the Colebrook-White equations in order to calculate wastewater velocity and depth in all pipes throughout the network at all time steps.

The sewer network used in this study, consisted of 3093 links, 3048 of which were sewer pipes (conduits) while the rest of the links were valves, pumps and other connections. There were 2296 sub-catchments which can contribute two types of flow. Most catchments contributed ‘foul’ (domestic wastewater inflow), as well as ‘trade’ flows, which referred to industrial inflows and occurred in a limited number of the catchments. Some of the pipes carrying trade flows did not contain flow at all timesteps, and occasionally there were flow reversals in this network. Hence, both zero and negative values of flow were possible in the hydraulic output from this Infoworks CS model. Therefore, the hydraulic output data was filtered by replacing zero and negative values of wastewater depth, velocity and flow with a very small positive default values (0.0001 m, m/s or m^3/s) to ensure the stability of the heat transfer modelling. This filtration process had an insignificant effect on the predicted total daily wastewater volume, the difference did not exceed 0.5% in January, March and May, while the adjustment of negative and zero wastewater level values accounted for less than 0.7% of the total values in the three months.

In this study only dry weather flow (DWF) conditions on working days was considered. The DWF days were selected by observing the flow variation plots in the measurement period for each site. The rainfall events were obvious, hence periods without rainfall that showed consistent flow patterns for a continuous period of three or more days were considered to be DWF days.

2.2.2 Building and calibration of the hydrodynamic model

Aquafin (2014) standards was utilised to construct the Infoworks CS model. The hydrodynamic model was built using historical datasets of the pipe geometries, characteristics and connectivity. This data was compared to records of the current state of the network and field observations and the model geometry was corrected when needed. The DWF at each model input node was estimated based on the local population equivalent (PE), the average wastewater production rate per person and an empirical diurnal wastewater profile. Trade flow was predicted from records of the maximum permitted industrial inputs. The diurnal variation in flow was calibrated using measured flow rates at seven locations across the network during two dry weather days.

2.2.3 Validation of the hydrodynamic model

A flow monitoring campaign was carried out specifically for this study that included the installation of flowmeters in seven locations across the sewer network. The modelled wastewater flow was visually compared with measured data based on time-series datasets and the total flow was checked against the measured downstream flow of the entire network. In cases where the observation showed large discrepancies (e.g. bias in wastewater depth greater than 2 cm), the model was updated by adjusting relevant parameters, such as the local and pipe head loss coefficients and the height of the fixed sediment layer, so that the modelled results better matched the observed data. An acceptable level of performance level was determined by an experienced hydrodynamic modeller through visual comparisons between modelled and monitored values of flow rates at the seven locations throughout the network.

2.3 The network heat transfer model

This model was created by developing and using the single pipe heat transfer model and linking this to the hydrodynamic model. The simulation of wastewater temperatures at all locations within a large sewer network was achieved by implementing the network heat transfer model. This section explains how the model was developed, used for identifying heat recovery locations and validated.

2.3.1 Development of the network heat transfer model

Three main datatypes were generated from the Infoworks CS model, these are: the details of the network links, hydraulic data and soil types. The details of the network links provided information on the way the links were connected, link type, geometry, dimension and the material of each link in the network. The link types mainly included conduits (pipes), valves and pumps, and each link had a unique identifier number which can be utilised to identify its streamwise location of the network. The hydraulic data consisted of the Infoworks CS modelled wastewater flow rate, velocity and depth in each link for a full year at two minute timesteps. Table 1 shows a summary of the data and pipe details retrieved from the hydrodynamic model and literature, in order to create the network heat transfer network model.

Table 1: Summary of the data used to create the network heat transfer model.

Category	Model input	Value / Range	Unit	Notes
Sewer temperatures	In-sewer air temperature	8.6 to 15.5	°C	Measured in the case study sewers during January, March and May 2012.
Hydraulic data for each pipe	Wastewater flow rate	0.0001 to 10.6	m^3/s	Full year Infoworks CS simulations, 2 minutes time step. Negative or zero values were replaced by 0.0001 m, m/s or m^3/s. Assumed stream-wise flow direction.
	Wastewater velocity	0.0001 to 2	m/s	
	Wastewater depth	0.0001 to 4.3	m	
Sub-catchments connected to the sewer network	Flow of wastewater discharged from trade	0.0001 to 0.007	m^3/s	Full year Infoworks CS data, 2 minutes time step.
	Flow of wastewater discharged from foul	0.0001 to 1.85	m^3/s	
	Trade wastewater temperature	15	°C	Assumed, based on model validation and agrees with Schilperoort & Clemens (2009) measurements.
	Foul (residential) wastewater temperature	15	°C	
Specifications of each sewer pipe	Sewer pipe shapes	Circle, egg or rectangular		Hydrodynamic model
	Sewer pipe materials	Concrete, steel, reinforced concrete, clay, brick, or polyvinyl chloride.		
	Sewer length	1 to 801	m	
	increment length stream-wise (Δx), based on diving each pipe into 10 increments	0.1 to 8	m	
	Sewer diameter	0.08 to 5.25	m	
	Sewer wall thickness	0.053 to 0.3	m	
Soil details	Soil type surrounding each pipe	Sand		Provided by the regional soil database.
	Soil temperature	9 & 10	°C	Measured in case study catchment.
Pipe linkages	Pipe identifiers	The unique pipe identifiers		Retrieved from the hydrodynamic model. The ids are used to organise the pipes in their stream-wise location and to connect incoming branches at the correct locations, and to connect the incoming foul, rainfall and trade flows in the right locations.
	Sub-catchment identifiers	The unique sub-catchment identifiers		

Equation 1 was used for each pipe in the network where the upstream temperature ($\overline{T_m}$) can correspond to either a 1st generation or 2nd and higher generation pipes. The different pipe generations reflect the streamwise locations of the pipe within the sewer network. Pipes of the 1st generation transport wastewater from the most upstream area of the network, e.g. foul or trade sub-catchments, to the 2nd generation pipes and consequently to the 3rd, 4th and up to the 7th generation pipes before reaching the WwTP. Figure 1 illustrates how the pipes were connected in the network at different generations. The wastewater temperature for the 1st generation pipes was assumed to be equal to that discharged from the relevant sub-catchment, while the upstream wastewater temperature for the 2nd and higher generations was assumed to be equal to that of the downstream temperature of the preceding generation. When more than one pipe was connected to one or more pipes, as shown by Figure 1, the upstream wastewater temperature was computed by Equations 6 and 7.

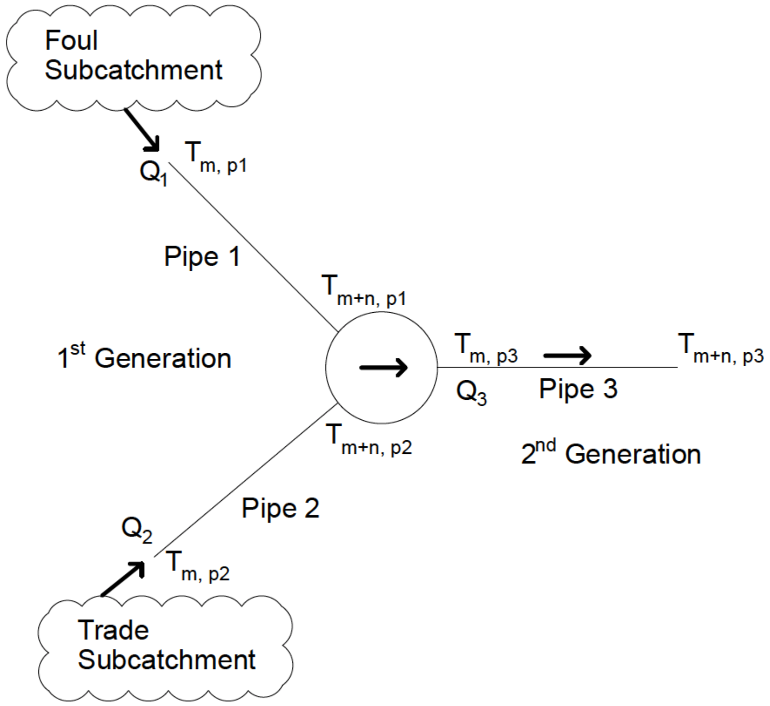


Figure 1: Example of two pipes connected to a third pipe in the sewer network. T_m and T_{m+n} are the pipe upstream and downstream wastewater temperatures respectively, n is the number of mesh points along the pipe length. p and T stand for pipe and wastewater temperature respectively. The flow is assumed to be heading into one direction shown by the arrows.

$$Q_3 = Q_1 + Q_2 \tag{6}$$

$$T_{m,p3} = \frac{T_{m+n,p1} \times Q_1 + T_{m+n,p2} \times Q_2}{Q_3} \tag{7}$$

where; T is temperature (K or °C) and p 1,2 & 3 refer to pipes 1, 2 & 3 respectively as illustrated in Figure 1. m is the mesh location of the predicted wastewater temperature along the pipe length, n is the number of mesh points along the pipe length.

Model input temperatures, i.e. of wastewater at the 1st generation pipes, soil and in-sewer air, can be retrieved from literature based on field seasonal data (see Table 1). The model output is the wastewater temperature variation along the length of each sewer pipe in the network, and the WwTP influent temperature. This paper's results will focus on the minimum wastewater temperatures in the network and on the WwTP influent to enable the assessment of the potential heat energy recovery from the sewer network.

Figure 2 summarises the process followed for developing the network heat transfer model, which was used in this paper.

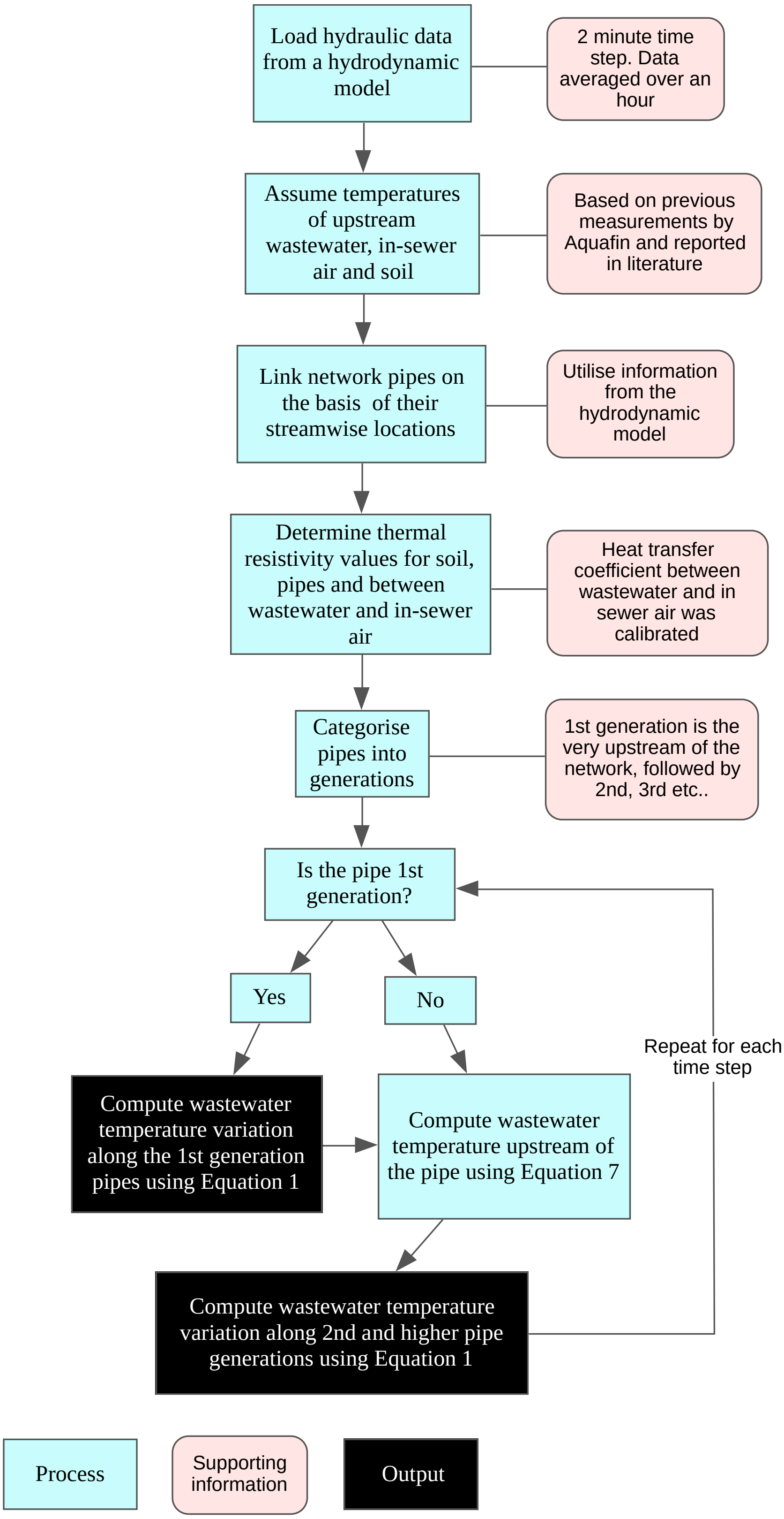


Figure 2: Flowchart of the process followed for the network heat transfer model development.

2.3.2 Determination of heat recovery locations

The heat energy recovery locations were determined by the network heat transfer model based on selection criteria for each sewer pipe determined by the model user, these are: defining a minimum wastewater temperature and a minimum flow rate. Section 2.5 explains the selection criteria used in this work to create the heat energy recovery scenarios.

2.3.3 Validation of the network heat transfer model

The network heat transfer model was validated using measured data in four different manhole locations within the case study 3000 pipe network. The same Tinytag sensors described in section 2.1.2 were used for the network model validation. Sewer pipes with different sizes and various streamwise locations were selected for validation to reflect the diverse pipe characteristics in a large sewer network. Locations 1 and 2 were 1st and 2nd generation sewer pipes respectively, while locations 3 and 4 were 3rd generation pipes, and distances between the four locations varied from 48 to 1600 meters. For effective data collection and sensor maintenance, the distances between monitored locations were relatively short to support Aquafin operators carry frequent site visits. Figure 3 shows the locations of the measured temperatures in the sewer pipes.

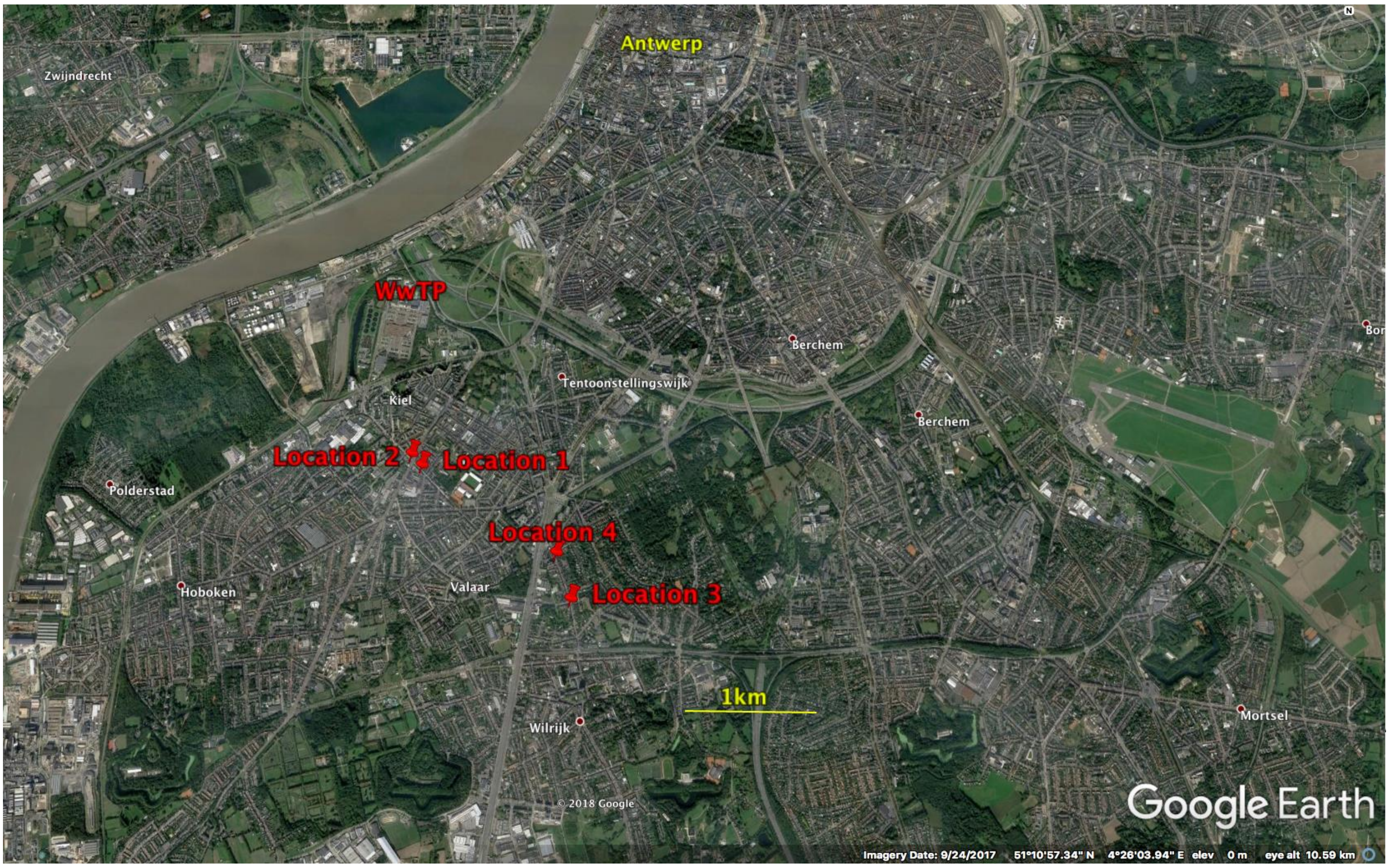


Figure 3: Locations of monitored sewer sites used to validate the network heat transfer model

Datasets used for validation were recorded on 16th January, 12th March and 5th May 2012. Hourly averages of the measured data were obtained and used for validating the network heat transfer model in each of the four locations. The network heat transfer model validation was based on the difference between measured and predicted wastewater temperatures on an hourly basis. The RMSE for each day (N=24) was also computed using Equation 5 to show the overall model daily performance. The network model error, defined as the hourly average predicted minus measured wastewater temperatures, was computed to investigate the model over and under prediction. A foul temperature of 15°C, which is within the range measured by Schilperoort and Clemens (2009), was used for validating the network model. This is considered to be a relatively low foul temperature, when compared with that measured by the aforementioned authors which reached 35°C, and hence the validated model represents challenging input boundary conditions for heat energy recovery applications.

2.4 Assessment of the heat energy recovery viability

The viability of heat energy recovery in this paper was assessed by predicting and examining the wastewater temperature in the sewer network and at the WwTP influent. The influent WwTP temperature can affect the nitrification quality as mentioned in Section 1, and the wastewater temperature in the sewer network needed to be well above the freezing point. Water utilities may have different regulations regarding thresholds for these temperatures. This paper measured the viability of heat energy recovery by referring to Aquafin's requirements regarding wastewater temperatures. Aquafin (2015) considers minimum wastewater temperatures of 5°C in the sewer network to be viable as long as the WwTP influent stays 9°C or above. Therefore, the aforementioned temperatures were assumed to be the thresholds criteria for a viable heat energy recovery option. These temperature thresholds can be varied by the model user to simulate the potential of heat recovery within the limits provided by the local regulations.

2.5 Heat energy recovery scenarios

Three scenarios were considered in this study to reflect extreme cold (January), cool (March) and moderate (May) weather conditions of the winter, spring and summer seasons. The three scenarios utilised hydraulic data from Infoworks CS. Apart from the variation in the hydraulic data, the main differences between the three scenarios were the measured in-sewer air and soil temperatures, which ranged between 8.6 and 15.5°C and between 9 and 10°C respectively. The calibrated heat transfer parameters were utilised for modelling each scenario. Table 3 lists the values of the heat transfer parameters used in each seasonal scenario.

The minimum wastewater flow criterion for a pipe to be qualified for a heat energy recovery location was set to be 25, 50, 100 & 200 L/s. Although some practitioners recommend minimum flow range of 10 to 15 L/s (DWA, 2009), the 25 L/s value was found to be appropriate in such a large sewer network. This is because the majority of the pipes in the sewer network would have a wastewater flow rate between 10 and 15 L/s during a DWF day, which would result in a very large number of heat recovery locations and consequently, wastewater temperature reductions would be too large. The values of 25, 50, 100 and 200 L/s were decided based on a number of trials. A minimum wastewater temperature for a pipe to be qualified for heat recovery was decided to be 9°C, which was equal to the minimum required for the WwTP influent. Table 2 describes the three scenarios and their relevant assumptions. A rate of 200 kW heat was assumed to be recovered from locations that meet the temperature and flow conditions set as minimum criteria. This assumption was based on a study performed by Vlario (2015) where estimates of the total conventional radiator capacity for 93 flats in Belgium were in the order of 200 kW. The DWF days were found consistent in terms of the wastewater flow variation, and hence, a random working day with DWF was selected in January, March and May to show the potential heat energy recovery and its implications on wastewater temperatures. Each of the three seasonal scenarios shows the potential of heat energy recovery during the selected day (00:00 AM to 23:59 PM) on an hourly basis.

Table 2: Scenarios of heat energy recovery in January, March and May using different measured temperatures of in-sewer air. HR is the rate of heat recovery.

Scenario	**Date in 2012**	**Time of HR on hourly basis**	**HR from pipes with**		**HR**	**Temperatures**			**Network flow**
			Min. Flow	**Min. Temp**		**Foul**	**In-sewer air**	**Soil**	
		hh:mm	L/s	°C	kW/pipe		°C		L/s
1	Monday 16th January	00:00 to 23:59		9			8.6 to 9.3	9	
2	Monday 12th March	00:00 to 23:59	25, 50, 100 & 200	9	200	15	9.7 to 10.8	9	0.1 to 340
3	Friday 4th May	00:00 to 23:59		9			13.7 to 15.5	10	

Hours between 07:00 and 08:00 AM had the highest heat energy demand in each of the scenario days, based on smart meter readings for 100 residential homes across the UK (AECOM, 2014). Therefore, to investigate the potential of heat recovery during DWF and relatively high heat demand conditions in more details, data between 07:00 and 08:00 AM was utilised to present model outcomes using probability distribution function (PDF) plots of minimum wastewater temperatures in the network.

3 Results

This section shows the calibrated parameters of the single pipe heat transfer model. The section then presents the validation results for the single pipe and network heat transfer models. The potential of heat energy recovery, on an hourly basis, in each scenario and the implications of this in terms of wastewater temperature variation are described in the final part of the section. The results of modelling each scenario, between 7:00 and 8:00 AM, are presented in more details through PDF plots and a summary table.

3.1 Calibration results for the single pipe heat transfer model

Table 3 shows the values of calibrated parameters used in the single pipe heat transfer model, in urban and large collector sewers.

Table 3: Values of calibrated parameters used in the single pipe heat transfer model. k_s and d_s are the soil thermal conductivity and its penetration depth respectively, h_{wa} is the heat transfer coefficient between wastewater and in-sewer air, R_{wa} and R_{ws} stand for thermal resistivity between wastewater and in-sewer air and soil respectively.

Month	k_s/d_s (W/m^2.K)		h_{wa} (W/m^2.K)		R_{wa} (m.K/W)		R_{ws} (m.K/W)	
	Residential	Collector	Residential	Collector	Residential	Collector	Residential	Collector
February	No data	100	No data	66	No data	0.02	No data	0.07
March	67	100	32	58	0.07	0.02	0.32	0.08
May	63	100	7	50	0.28	0.03	0.31	0.08

The calibrated parameters showed different values for different months and site characteristics, particularly h_{wa}. This is likely to be due to the seasonal differences in the thermophysical properties of the in-sewer air and soil caused by the temperature variation which would influence their thermal conductivity. This effect was also described in Abdel-Aal (2015). Although groundwater level may influence the soil temperature, measured data showed soil temperatures in the case study catchment did only vary slightly, by 1 °C. This may be due to the existence of groundwater, which its level was not measured.

3.2 Validation results for the single pipe heat transfer model

The calibrated heat transfer coefficient between wastewater and in-sewer air improved the modelling accuracy, where the monthly RMSE obtained previously using the Flinspach (1973) relation was up to 0.83°C (Abdel-Aal, 2015) while implementing the new parameterisation on the same sewer pipe using an identical validation method showed RMSE values of 0.13°C (February), 0.43°C (March) & 0.28°C (May). The monthly modelling errors in the validated model, for a single pipe, ranged between -0.17 and 0.09°C in winter and between -0.04 and 0.06°C in summer. The ranges of the modelling errors indicate over and under prediction in each sewer pipe, which minimise the overall error in the predicted wastewater temperatures across the network since the error is unlikely to accumulate. Based on the modelling errors, the resolution for temperature results is reported to the nearest one decimal place.

3.3 Validation results for the network heat transfer model

Validation of the network heat transfer model resulted in daily RMSE values that varied from 0.44°C in May, 0.45°C in January to 0.72°C in March, which can be considered reasonable for the model purpose of assessing the potential of heat recovery from sewer networks. The relatively high RMSE in March is likely due to the larger temperature fluctuations in the day which varied by 4°C, compared to 2°C in January and May. The mechanism of heat transfer is affected by the seasonal temperature variation and hence, calibrating heat transfer parameter under such large temperature variation, in March, is expected to produce discrepancy in predicted results.

The hourly modelling errors varied between -0.60 to 0.87°C in January, -0.76 to 1.2°C in March and -1.2 to 0.90°C in May. Similar error implications to that found in the single pipe heat transfer model validation, the errors in predicted wastewater temperatures, across the network, is likely to be reduced since the model under and over predicts, shown by the negative and positive modelling errors respectively, in the three seasons.

3.4 Scenarios 1, 2 & 3, heat energy recovery between 00:00 & 23:59 PM

Figure 4 shows the potential of heat energy recovery on an hourly basis over a day in January, March and May, the minimum network temperatures and corresponding WwTP influent temperatures. The points plotted in Figure 4 reflect the network heat transfer model outcomes for 200 kW/pipe heat recovered from pipes with flow rates higher than 25, 50, 100 & 250 L/s, during 24 hour periods in January, March and May. The DWF variation along the day of each scenario was found to be consistent in each month. It was also noticed that DWF reached its minimum value during the hours between 03:00 AM and 04:00 AM and was almost constant otherwise.

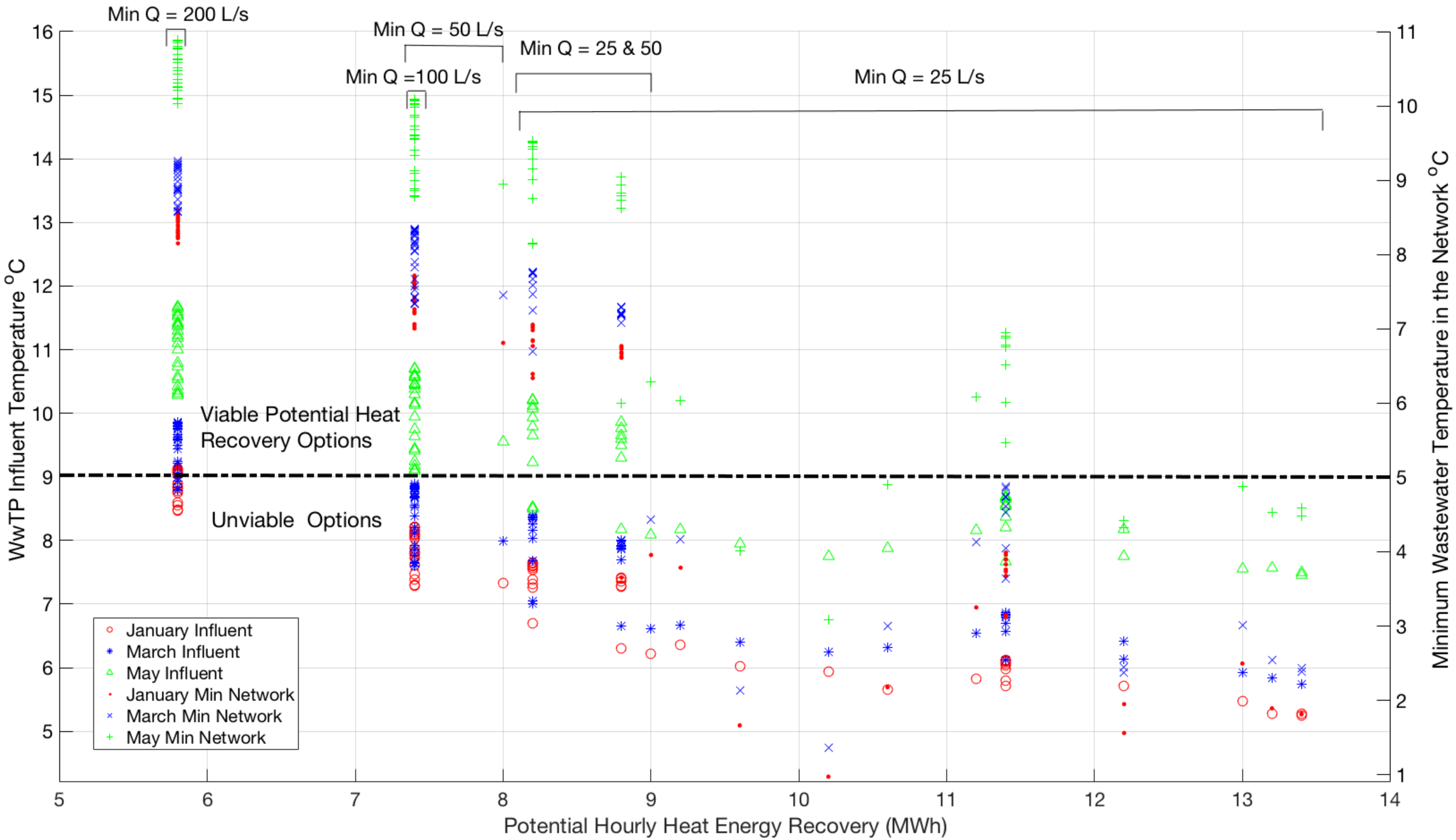


Figure 4: Potential heat energy recovery options, WwTP influent temperatures (left axis) and minimum wastewater temperatures in the network (right axis) in January, March and May, when 200 kW/pipe is recovered from pipes with flow rates higher than 25, 50, 100 & 200.

The maximum potential heat energy that can be recovered from the sewer network, over an hour, was 13.4 MWh for January, March and May. One can notice, from Figure 4, the impact of this 13.4 MWh recovery on the WwTP influent temperature, which varied from 5.3°C (January), 5.7°C (March) to 7.5°C (May). Higher values for the minimum required pipe flow (e.g. 200 L/s) to recover 200 kW/pipe presented lower number of locations, which estimated less potential heat energy recovery. This is expected since 97% of the sewer pipes in the network had flow rates less than 27 L/s. In this work, heat energy recovery is considered viable only when the WwTP influent is above or equal to 9°C and minimum wastewater temperature in the sewer network is 5 °C. Such viable options were presented by the 133 points (out of 288) plotted above the dash dotted line in Figure 4. The network heat transfer model predicted 116, 160 & 207 MWh/day to be recovered in January, March and May respectively. The latter predictions of heat energy recovery are the total of maximum hourly values that were considered viable for each day.

The time of the day had a noticeable effect on the rate of heat recovery and minimum wastewater temperatures in the network and at the WwTP influent due to the variation of the DWF along the day. In January, viable heat recovery was predicted to be possible during the time periods from midnight to 01:00 AM, and between 06:00 AM and 23:00 PM, in March it was from midnight to 02:00 AM and between 05:00 AM and 23:00 PM, whilst in May viable heat recovery was possible in all the 24 hours period. Figure 5 shows the potential heat energy recovery on an hourly basis along the 24-hour periods in January, March and May. The rate of potential heat recovery, at a particular time of the day, was the same in each month, hence Figure 5 only shows the results of the January scenario. The relatively low flow rate between 03:00 and 04:00 AM resulted in a smaller number of locations (41), which was much lower than other cases, e.g. 67 potential locations were identified between 10:00 and 11:00 AM in the three scenarios for heat recovery from pipes with minimum flow of 25 L/s. Therefore, the maximum heat recovered between 03:00 and 04:00 AM was 8.2 MWh which was less than that of 13.4 MWh predicted between 10:00 and 11:00 AM. Nevertheless, the minimum WwTP influent temperature in January, between 03:00 and 04:00 AM, was higher (8 °C) than that between 10:00 and 11:00 AM (7 °C), and similarly, the minimum network temperature was always above 6°C between 3:00 and 04:00 AM, which was much higher than its 1.8°C equivalent obtained between 10:00 and 11:00 AM.

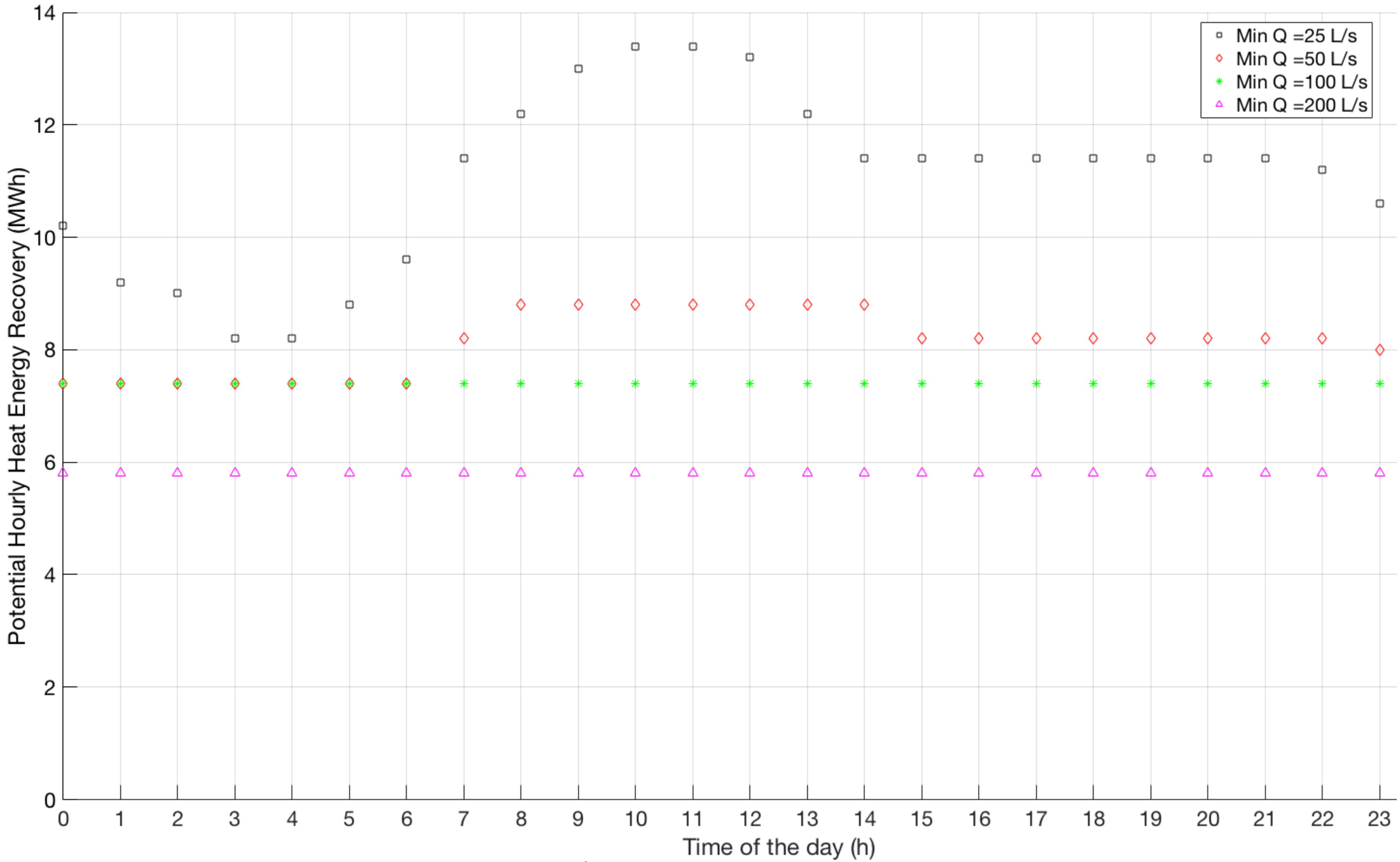


Figure 5: Potential heat energy recovery on hourly basis in 16th January. Other months showed the same hourly heat energy recovery.

3.5 Scenarios 1, 2 & 3: heat energy recovery between 07:00 & 08:00 AM

This section shows the PDF of minimum network temperatures for each scenario between 07:00 & 08:00 AM and summarises the outcomes of the modelled scenarios during the selected hour. The area under the curve between two temperature points, in a PDF plot, would indicate the probability of having pipes with temperature values corresponding to these points. The PDF was also plotted for the sewer network when there was no heat recovery; to enable the comparison with the heat recovery scenarios. For effective utilisation of the thermal energy content in the sewer network, an ideal scenario would show a shift towards the left, relative to the 'no heat recovery' PDF, while maintaining the network temperature thresholds.

3.5.1 Scenario 1, between 07:00 & 08:00 AM

Figure 6 shows the PDF of wastewater temperature at the downstream end of each pipe in Scenario 1 between 7:00 and 8:00 AM. Recovering heat in Scenario 1 would reduce the wastewater temperatures in the network, which was evidenced by Figure 6 showing higher probabilities of wastewater temperatures being between 10 and 12°C than that when no heat was recovered.

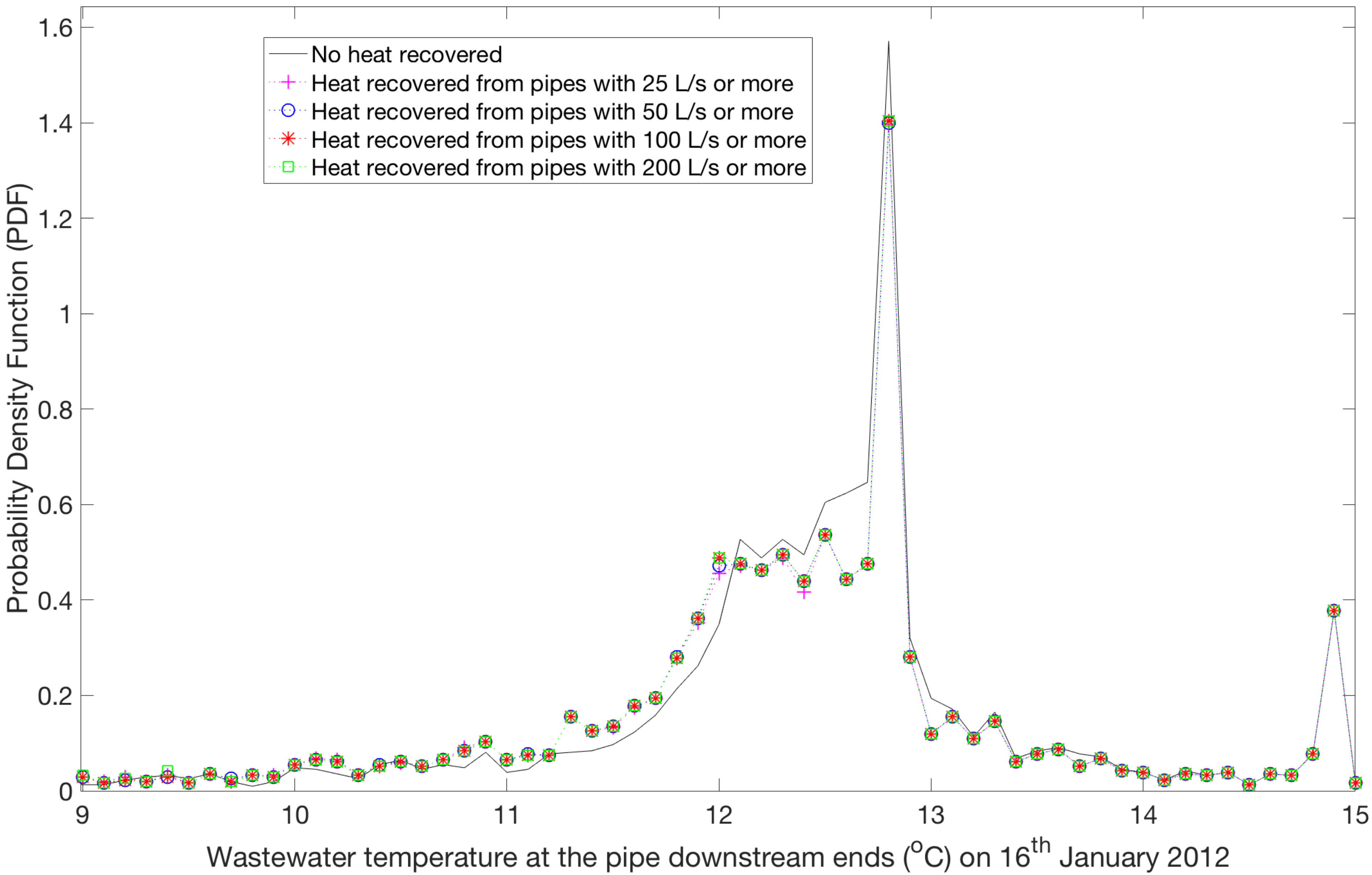
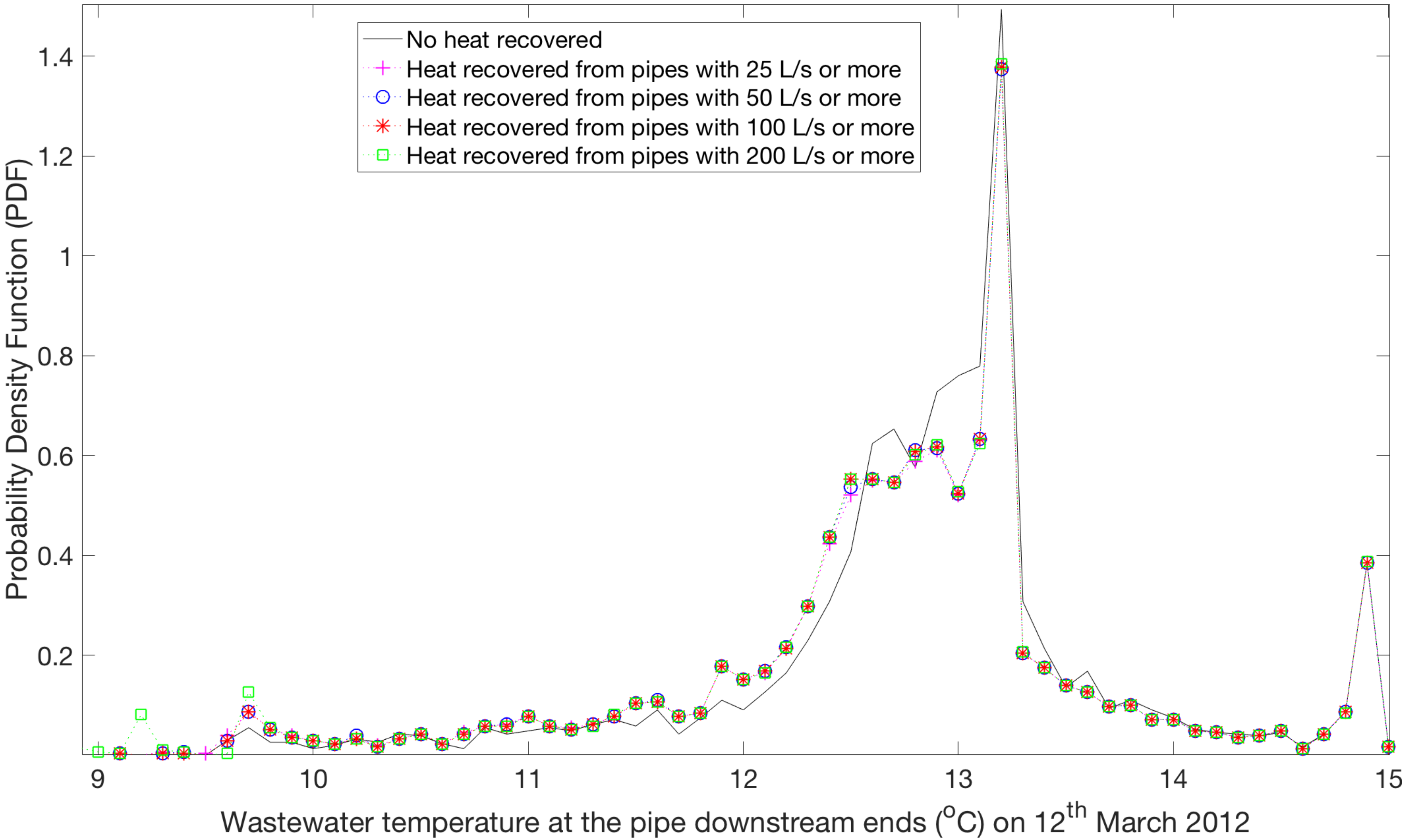


Figure 6: Probability distribution function (PDF) of the pipe downstream wastewater temperature, when heat is recovered in January, between 07:00 and 08:00 AM (Scenario 1). The PDF of temperatures below 9 °C was equal/close to zero, and hence neglected in the plot.

3.5.2 Scenario 2, between 07:00 & 08:00 AM

Figure 7 shows the PDF of wastewater temperatures, at the downstream ends of each pipe in Scenario 2 between 07:00 and 08:00 AM. The heat energy recovery resulted in slightly larger probability of pipes with temperatures between 11 and 12.3 °C.



525 *Figure 7: Probability distribution function (PDF) of the pipe downstream wastewater temperature, when heat is recovered in March, between 07:00 and 08:00 AM (Scenario 2). The PDF of temperatures below 9℃ was equal/close to zero, and hence neglected in the plot.*

3.5.3 Scenario 3, between 07:00 & 08:00 AM

Figure 8 shows the PDF of pipe downstream wastewater temperatures in Scenario 3, between 07:00 and 08:00 AM. As expected, heat energy recovery in May results in generally higher temperatures compared to Scenarios 1 and 2, and increased the probability of obtaining lower pipe temperatures (between 13.7 and 14.3 °C) than that of no heat recovery.

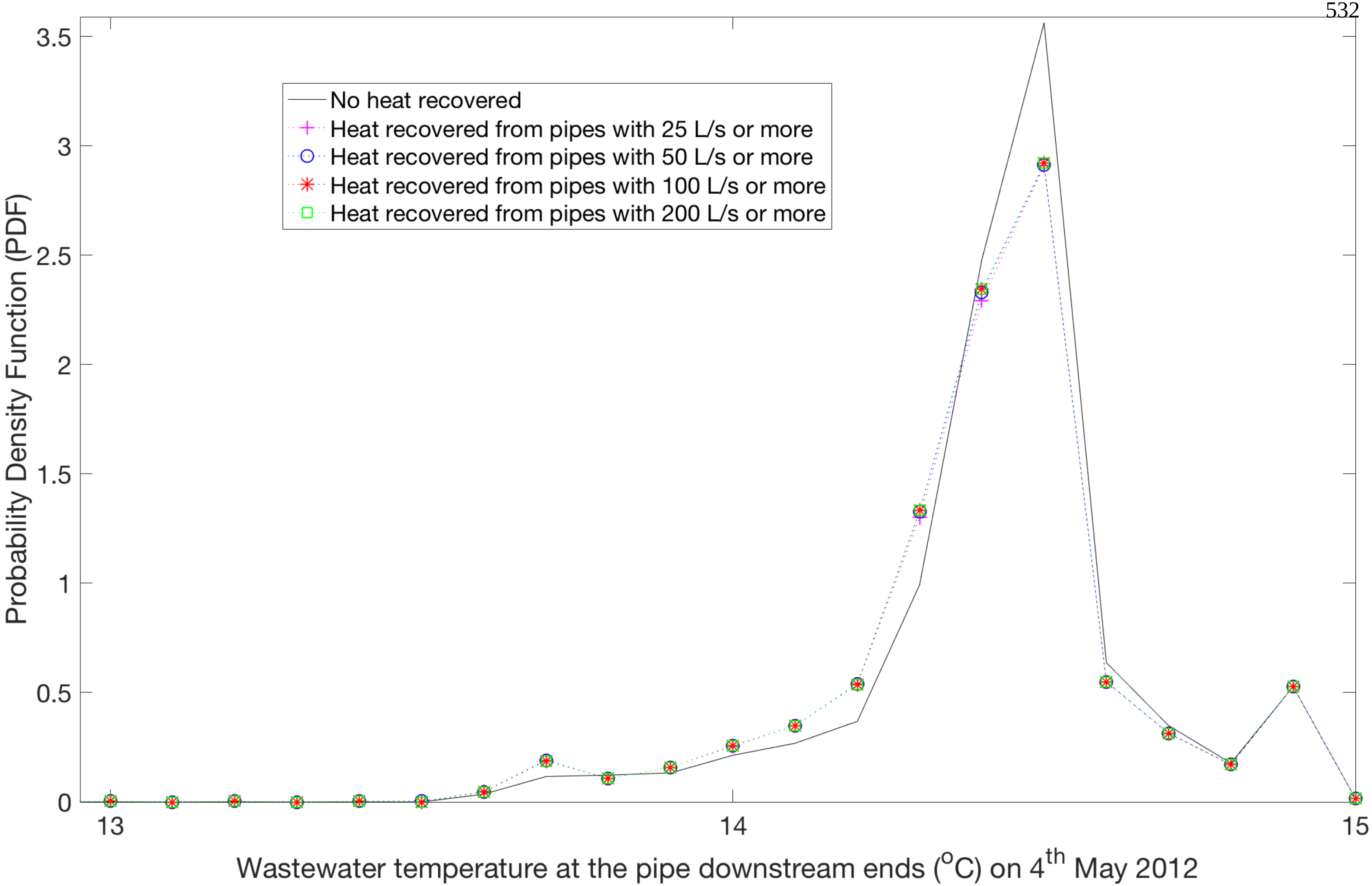


Figure 8: Probability distribution function (PDF) of the pipe downstream wastewater temperature, when heat is recovered in May, between 07:00 and 08:00 AM (Scenario 3). The PDF of temperatures below 13 ℃ was equal/close to zero, and hence neglected in the plot.

3.5.4 Summary of Scenarios 1, 2 & 3, between 07:00 & 08:00 AM

Table 4 summarises the findings of Scenarios 1, 2 and 3 for the hours between 07:00 and 08:00 AM. The number of locations in Table 4 refers to the number of pipes that meet the temperature (above 9°C) and the flow (25, 50, 100 & 200 L/s or above) criteria for recovering heat (200 kW/pipe). The total heat energy recovery for each of the three scenarios was the same for each criterion, since the number of potential locations was the same. The three scenarios, presented in this section, demonstrated five potentially viable heat energy recovery options where the minimum temperatures were above the thresholds.

The minimum influent temperature was around 3°C below the 9°C threshold while the temperatures in some pipes fell 2°C below the 5°C threshold.

Table 4: Summary of potential heat energy recovery results from Scenarios 1, 2 and 3 between 7:00 and 8:00 AM. HR stands for heat recovery.

Scenario	Month	Min Q	No. of HR locations, between 07:00 and 08:00 AM	Total HR between 07:00 and 08:00 AM (200kW/pipe)	WwTP Influent temperature Before HR	Minimum network temperature Before HR	WwTP Influent temperature After HR	Minimum network temperature After HR
		L/s		MWh	°C	°C	°C	°C
1	January	25	57	11.4	12.5	8.6	5.7	3.1
		50	41	8.2			7.3	6.8
		100	37	7.4			7.8	7.4
		200	29	5.8			9.0	8.5
2	March	25	57	11.4	13.0	9.7	6.1	3.6
		50	41	8.2			7.7	7.2
		100	37	7.4			8.2	7.8
		200	29	5.8			9.2	8.9
3	May	25	57	11.4	14.5	13.7	7.7	5.5
		50	41	8.2			9.2	8.7
		100	37	7.4			9.7	9.3
		200	29	5.8			10.8	10.3

4 Discussion

Linking a single pipe heat transfer model to a hydrodynamic model and validating the linked model in a sewer network setting enabled the investigation of potential multi-location heat energy recovery from a sewer catchment of 79500 PE. The viable potential heat energy recovery options varied depending on the month, where the lowest predicted was 116 MWh/day or 42 GWh/year, assuming a 100% efficient heat recovery system. This potential viable heat energy is adequate to cover the annual heat demands of 2500, 3500 or 5300 households, assuming high, medium and low UK annual gas consumption of 17, 12 and 8 MWh/household respectively (Ofgem, 2017 and Ali et al., 2017). March and May showed potential viable heat energy recovery of 58.4 and 75.7 GWh/year, that are equivalent to annual heat demands of 4900 and 6300 households respectively when considering the medium demand of 12 MWh/year/household. Accounting for the lowest potential heat energy recovery (January) and the range of annual household demand, 7 to 15% of the 79500 PE catchment annual demand can be met, without causing wastewater temperatures in the network or in the WwTP influent to be below 5 and 9°C respectively, assuming 2.3 PE per household. The above percentage may rise to cover 14% and 18% of the catchment heat annual demand when March and May scenarios are considered respectively, assuming medium annual UK heat demand.

The rates of predicted heat recovery were presented in more details for the hours between 07:00 and 08:00 AM since this is considered to be the time for high heat energy demand and showed typical representation of the daily DWF. Prediction results showed that setting a low flow threshold level for pipes to recover heat from (e.g. 25 L/s), larger rates of heat can potentially be recovered, which consequently resulted in lower wastewater temperatures (Figure 7 & Figure 8). This was expected since the lower flow rate had less thermal capacity and hence caused a larger wastewater temperature reduction in sewers (Equation 1). One can notice a shift in the PDF peaks from left (low temperature) in January to the higher temperatures in May. This is due to the higher in-sewer air temperature (around 14.4°C) in May which was highly influenced by the ambient air temperature. Table 4 showed how recovering heat of 5.8 to 8.2 MWh, in Scenarios 1, 2 and 3 can be achieved while meeting the minimum temperature criteria set by the water utility.

Other studies have suggested that heat recovery from wastewater may reduce the deposition of fat, oil and grease (FOG) (He, et al., 2017). This is because temperature plays a major part in influencing the FOG hydrolysis rate where higher temperatures increase the rate of saponification, which increases the FOG deposition (Iasmin, et al., 2016). However, the latter authors performed their study on temperatures of 22 and 45°C, hence further research is needed to investigate the impact of temperature variation, over a more typical in-sewer temperature range (e.g. 5 to 25°C), on the FOG deposit formation.

This paper has not considered the practical barriers of recovering heat from a sewer network. For example, there are physical limitations on the possibility of installing heat exchangers in certain pipe sizes, which is dependent on the rate of heat recovery. Future work will implement a multi criteria optimisation technique to maximise the potential of heat energy recovery, within a sewer network, without compromising on the wastewater treatment process, and taking into account practical issues associated with the location and operation of heat exchangers.

5 Conclusions

A network heat transfer model, was developed and validated in this study and was implemented to assess the viability of heat energy recovery scenarios, from a large Belgian sewer network serving 79500 PE. The network heat transfer model was based on single pipe heat transfer model, which utilised the first principles of heat transfer including the heat exchange between wastewater and in-sewer air, and was linked to a hydrodynamic model to predict wastewater temperatures throughout the network over extended periods. Validation of the network heat transfer model showed a daily RMSE between measured and modelled in-pipe wastewater temperatures that ranged between 0.44 and 0.72 °C for the different months of the year. This was based on a constant input foul temperature of 15°C, which minimised the RMSE of the measured and modelled in-pipe wastewater temperatures. Three modelled seasonal scenarios showed potential heat energy recovery options on an hourly basis in three days with dry weather flow during January, March and May. It was found that 46% of the 288 hourly modelled heat recovery simulations predicted viable heat recovery since they resulted in wastewater temperatures that were always equal or above the thresholds of 5 °C, in the network, and 9 °C in the WwTP influent. The predicted rate of heat energy recovery whilst meeting the minimum temperature requirements varied from 116 MWh/day in January to 207 MWh/day in May. This can meet 7% to 18% of the 79500 PE catchment heat demand, assuming a 100% efficient heat recovery and supply system. The current network heat transfer model will be further developed to enable the automated spatial optimisation of viable heat recovery locations from a large sewer network given both practical constraints and the wish to achieve the highest heat recovery that satisfies local demand. Future studies may also examine the temporal availability of heat and whether the rate of heat recovery can be enhanced by better matching the temporal pattern of local heat demand and recovery.

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